

# Direct and indirect detection of higgsino-like WIMPs: concluding the story of electroweak naturalness

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## Abstract

Supersymmetric models which fulfill the conditions of electroweak naturalness generally contain light higgsinos with mass not too far from  $m_h \simeq 125$  GeV, while other sparticles can be much heavier. In  $R$ -parity conserving models, the lightest neutralino is then a higgsino-like WIMP (albeit with non-negligible gaugino components), with thermal relic density well below measured values. This leaves room for axions to function as co-dark matter particles. The local WIMP abundance is then expected to be below standard estimates, and direct and indirect detection rates must be accordingly rescaled. We calculate rescaled direct and indirect higgsino-like WIMP detection rates in SUSY models that fulfill the electroweak naturalness condition. In spite of the rescaling, we find that ton-scale noble liquid detectors can probe the entire higgsino-like WIMP parameter space, so that these experiments should either discover WIMPs or exclude the concept of electroweak naturalness in  $R$ -parity conserving natural SUSY models. Prospects for spin-dependent or indirect detection are more limited due in part to the rescaling effect.

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# 1 Introduction

The recent discovery of a Higgs-like resonance by Atlas and CMS collaborations[1, 2] at  $m_h \simeq 125$  GeV seemingly adds another supporting pillar to the theory of weak scale supersymmetry, since in the Minimal Supersymmetric Standard Model (MSSM)[3] we expect  $m_h \simeq 115 - 135$  GeV[4]. Aside from solving the gauge hierarchy problem, previous supporting pillars arising from data include 1. the measured values of gauge couplings allow for gauge coupling unification at a scale  $Q \simeq 2 \times 10^{16}$  GeV within the MSSM, 2. the large value of the top quark mass is precisely what is needed to drive electroweak symmetry breaking via radiative corrections and 3. SUSY is replete with several possible cold dark matter (CDM) candidates (neutralino/WIMP, gravitino, axino) in the form of the lightest SUSY particle (LSP).

Since a variety of SUSY model parameters enter into the scalar potential of the theory, and thus contribute to the  $W$ ,  $Z$  and Higgs masses, it is widely expected that superpartners should exist at or around the weak scale. This mantra has been repeated in numerous talks and papers over the past decades, so we refer to it here as the story of SUSY electroweak naturalness<sup>1</sup>. Indeed, the concept of naturalness may dictate to some degree when it is time to give up on weak scale supersymmetry should no signal be ultimately found[5].

While the existence of a Higgs-like scalar at  $\sim 125$  GeV is a boon for SUSY models, on the contrary, no signal for superpartners has yet emerged at LHC. In models such as the popular mSUGRA/CMSSM[6], the Atlas and CMS collaborations[7, 8] now require  $m_{\tilde{g}} \gtrsim 1.4$  TeV for  $m_{\tilde{q}} \sim m_{\tilde{g}}$  and  $m_{\tilde{g}} \gtrsim 1$  TeV for  $m_{\tilde{q}} \gg m_{\tilde{g}}$ . Already this fact has led some astute physicists to give up on weak scale SUSY[9], or to at least concede that weak scale SUSY is finetuned. Thus, the recent LHC limits on sparticle masses seemingly exacerbate what is known as the Little Hierarchy Problem (LHP): why is there such a disparity between the sparticle mass scale and the electroweak scale?

Before jumping to conclusions, it pays to scrutinize electroweak naturalness more closely. We can be more precise if we re-phrase the LHP in the following terms: how is it that the  $Z$ -boson mass can exist at just 91.2 GeV while gluino and squark masses are at, or even well beyond, the TeV scale? The answer proposed in Ref's [10, 11, 12] is that all the individual *weak scale* contributions feeding mass into  $m_Z$  should be not too far from  $m_Z$ . The value of  $m_Z$  in the MSSM is given by

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2, \quad (1)$$

where the latter approximate equality obtains for ratio-of-Higgs vevs  $\tan \beta \equiv v_u/v_d \gtrsim 3$  and where the  $\Sigma_u^u$  and  $\Sigma_d^d$  terms represent the sum of various radiative corrections[12]. To be quantitative, a finetuning measure

$$\Delta_{EW} = \max_i \left| C_i / (m_Z^2/2) \right| \quad (2)$$

may be defined, where  $C_i$  represents any of the terms on the right-hand-side of Eq. 1 (*e.g.*  $C_{H_u} \equiv -m_{H_u}^2 \tan^2 \beta / (\tan^2 \beta - 1)$  and  $C_\mu \equiv -\mu^2$ ). The finetuning measure  $\Delta_{EW}$  enjoys several

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<sup>1</sup> We thank Yuri Gershtein for making this point

advantages as discussed in Ref. [12]: it is 1. model-independent (within the MSSM) in that any model giving rise to the same weak scale SUSY spectrum will have the same measure of finetuning, 2. conservative, 3. unambiguous, 4. predictive, 5. falsifiable and 6. simple to encode.

In the 2-parameter non-universal Higgs model (NUHM2)[13], with parameter space given by

$$m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A, \quad (3)$$

scans have found that values of  $\Delta_{EW}$  as low as  $\sim 10$  (corresponding to  $\Delta_{EW}^{-1} \sim 10\%$  electroweak finetuning) could be found[10, 12]. To achieve low  $\Delta_{EW}$ , one needs a)  $|\mu| \sim m_Z \sim 100 - 200$  GeV, b)  $m_{H_u} \sim (1 - 2)m_0$  so that  $m_{H_u}^2$  is driven radiatively (via the large top-quark Yukawa coupling) to small but negative values at the weak scale and c) moderate values of  $m_{1/2} \sim 0.3 - 1$  TeV. Scalar masses may exist in the range 1-10 TeV (even higher if one allows for split generations) although large trilinear soft breaking terms  $A_0 \sim 1.5m_0$  are required. The large  $A$ -terms yield large mixing in the top-squark sector which simultaneously softens the radiative corrections  $\Sigma_u^u(\tilde{t}_1)$  and  $\Sigma_u^u(\tilde{t}_2)$ , while lifting the value of  $m_h$  into the 125 GeV range[10]. While the NUHM2 model admits values of  $\Delta_{EW}$  even below 10, the mSUGRA/CMSSM model is considerably more tuned, where a minimum  $\Delta_{EW} \sim 100$  has been found, although typically  $\Delta_{EW}$  for mSUGRA is more like  $10^3 - 10^4$ . Models with low  $\Delta_{EW} \lesssim 30$  have been dubbed *radiative natural SUSY* (RNS) since the low electroweak finetuning is radiatively driven.

The sparticle spectra found for RNS models with  $\Delta_{EW} \lesssim 30$  is characterized by:

- light higgsino-like  $\tilde{W}_1^\pm$  and  $\tilde{Z}_{1,2}$  with masses  $\sim 100 - 300$  GeV,
- gluinos with mass  $m_{\tilde{g}} \sim 1 - 4$  TeV,
- top squarks with  $m_{\tilde{t}_1} \sim 1 - 2$  TeV and  $m_{\tilde{t}_2} \sim 2 - 5$  TeV,
- first/second generation squarks and sleptons with masses  $m_{\tilde{q},\tilde{\ell}} \sim 1 - 8$  TeV. The  $m_{\tilde{q},\tilde{\ell}}$  range can be pushed up to 20-30 TeV if non-universality of generations with  $m_0(1,2) > m_0(3)$  is allowed.

The RNS model with the above spectra yields branching fractions  $BF(b \rightarrow s\gamma)$  and  $BF(B_s \rightarrow \mu^+\mu^-)$  in accord with measured values, unlike many models with lighter top squarks[14].

As far as testability goes, RNS models should yield observable signals from gluino pair production at LHC14 with  $\sim 300 \text{ fb}^{-1}$  for  $m_{\tilde{g}} \lesssim 1.6$  TeV[15]. The LHC14 reach for SS diboson production from  $pp \rightarrow \tilde{W}_2^\pm \tilde{Z}_4 \rightarrow W^\pm W^\pm + \cancel{E}_T$  gives a reach in terms of  $m_{\tilde{g}}$  of  $m_{\tilde{g}} \sim 1.8$  TeV for the same integrated luminosity[16]. Since  $m_{\tilde{g}}$  can range up to  $\sim 4$  TeV for the RNS models, then LHC14 will not be able to definitively discover/exclude RNS.

Alternatively, the hallmark distinction of RNS models is the presence of four light higgsinos with masses  $\sim 100 - 300$  GeV. A linear  $e^+e^-$  collider operating at  $\sqrt{s} \gtrsim 2|\mu|$  can definitively discover/exclude RNS models, *e.g.*  $\sqrt{s} \sim 0.5$  (1) TeV would access all models with  $\Delta_{EW} \lesssim 25$  (70). Since the timescale for operation of a TeV-scale ILC is of order 10-20 years, here we address instead the possibility of much earlier discovery of the higgsino-like WIMPs expected from RNS models.

## 2 Direct and indirect higgsino detection

In this paper, we generate RNS models from the Isasugra spectrum generator[17] using the same NUHM2 parameter space scan as utilized in Ref. [12]. We will require that the model generated from each parameter set obeys the LEP2 bound that  $m_{\tilde{W}_1} > 103.5$  GeV, and will focus on models with  $\Delta_{EW} < 50$  (100) corresponding to better than 2% (1%) electroweak finetuning. We calculate the “standard thermal neutralino abundance”  $\Omega_{\tilde{Z}_1}^{std} h^2$  using the IsaReD[18] relic density subroutine.<sup>2</sup> We will accept only models with  $\Omega_{\tilde{Z}_1}^{std} h^2 < 0.12$  for reasons to be made clear shortly. The relic abundance from RNS models is shown in Fig. 1. The red crosses have  $\Delta_{EW} < 50$  whilst blue dots have  $\Delta_{EW} < 100$ . Green points we will find later are already excluded by direct/indirect WIMP search limits. From the figure, we see a high density band extending from  $\Omega_{\tilde{Z}_1}^{std} h^2 \sim 0.004$  for  $m_{\tilde{Z}_1} \sim 100$  GeV to  $\Omega_{\tilde{Z}_1}^{std} h^2 \sim 0.02$  for  $m_{\tilde{Z}_1} \sim 300$  GeV, *i.e.* there is typically a standard *underabundance* of higgsino dark matter compared to measurement from WMAP9[19] by a factor ranging from 3-25. There is some spread in these values above and below the main band from cases where  $\mu$  is quite large and  $m_{1/2}$  is small so that one has instead a mixed higgsino-bino LSP state. The bulk of points above the band are already excluded as we shall see. Thus, the mainly higgsinolike neutralino by itself does not make a good CDM candidate. Additional new physics is needed to match the measured dark matter density.

One compelling way to address the dark matter deficiency is by invoking the Peccei-Quinn-Weinberg-Wilczek solution to the strong CP problem[20] via introduction of a PQ symmetry and concomitant *axions*. Since we are working in SUSY models, the axion will be accompanied by *R*-parity-even spin-0 saxions  $s$  and *R*-parity-odd spin- $\frac{1}{2}$  axinos  $\tilde{a}$ [21]. In gravity-mediation models (as assumed here), the saxion and axino are expected to have masses  $m_s \sim m_{\tilde{a}} \sim m_{3/2} \sim 5 - 20$  TeV[22], the same mass scale as matter scalars  $m_0$  in the theory. In this case, the dark matter would consist of both axions and higgsinos acting as co-dark matter particles.

The relic abundance of mixed axion-neutralino CDM has been addressed in Ref’s [23, 24, 25, 26]. In [26], it was found that SUSY models with a standard overabundance of dark matter are *still excluded* in the PQMSSM by a combination of dark matter overabundance constraints, BBN constraints and dark radiation constraints. However, SUSY models with a standard underabundance of neutralinos are still allowed over large ranges of PQMSSM parameters. For models with a standard underabundance, then thermal production and decay of axinos in the early universe augments the neutralino abundance, sometimes by too much, other times not enough: the former case would be excluded whilst in the latter case, the remaining abundance is made up of relic axions produced through the usual vacuum misalignment mechanism. In addition, for large values of PQ breaking scale  $f_a \sim 10^{13} - 10^{16}$  GeV, then saxions can be produced at large rates via coherent oscillations. The saxions can augment the neutralino abundance by decaying to SUSY particles (*e.g.*  $s \rightarrow \tilde{g}\tilde{g}$ ), or they can dilute all relics if they decay after freezeout into SM particles. Saxions may also decay into axion pairs  $s \rightarrow aa$  leading to production of dark radiation[27]. From the PQMSSM scans in Ref. [26], it is found that in the case where  $s \rightarrow aa$  branching fraction is at all substantial, then entropy dilution is

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<sup>2</sup>The standard thermal abundance refers to the neutralino density derived from assuming neutralinos in thermal equilibrium at high temperature followed by freeze-out due to the Universe’s expansion.

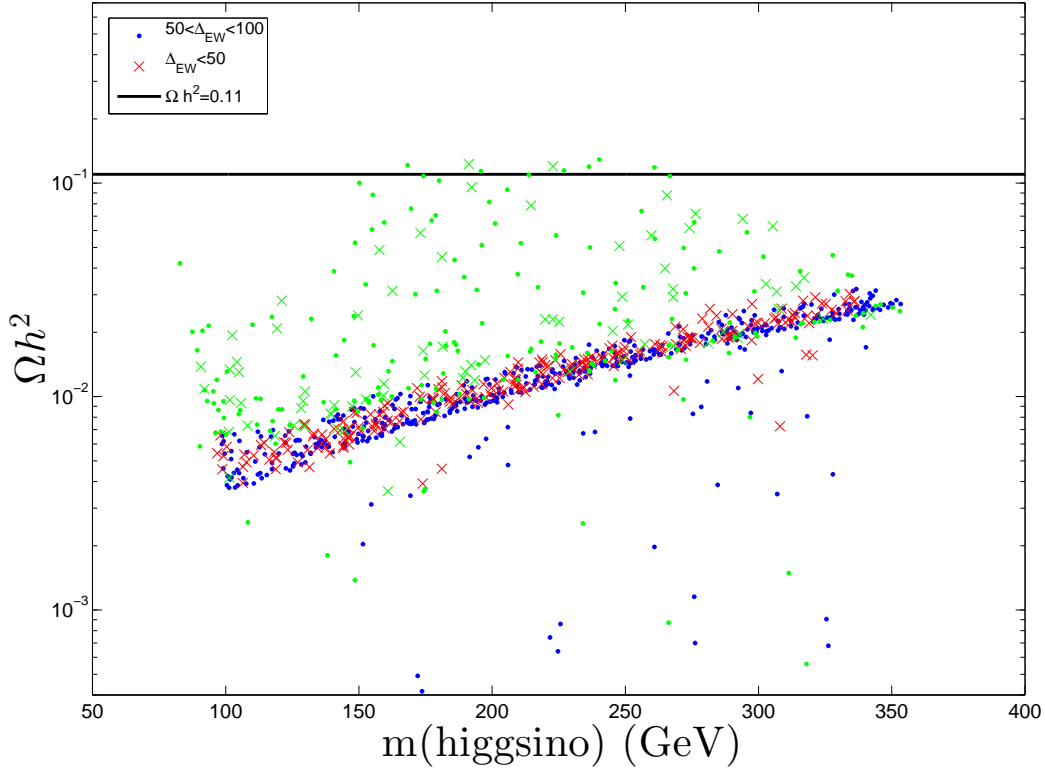


Figure 1: Plot of standard thermal neutralino abundance  $\Omega_{\tilde{Z}_1}^{std} h^2$  versus  $m(\text{higgsino})$  from a scan over NUHM2 parameter space with  $\Delta_{EW} < 50$  (red crosses) and  $\Delta_{EW} < 100$  (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show the central value of  $\Omega_{CDM} h^2$  from WMAP9.

always accompanied by a violation of either BBN or dark radiation constraints (parametrized by  $\Delta N_{eff} \gtrsim 1.6$  where  $\Delta N_{eff}$  is the effective number of additional neutrinos beyond the SM value). Thus, the scans over PQMSSM parameter space in Ref. [26] find that the standard underabundance can be augmented by any factor leading to  $\Omega_{\tilde{Z}_1}^{std} h^2 < \Omega_{\tilde{Z}_1} h^2 < 0.11$ , but not diminished without violating BBN or DR constraints. Models with too much CDM production, or models which violate BBN or dark radiation constraints would be excluded. The upshot is that in RNS models, for any particular parameter set, we expect the relic higgsino abundance to lie somewhere between the standard value  $\Omega_{\tilde{Z}_1}^{std} h^2$  (which would correspond to axion domination) up to the measured value 0.11, in which case CDM would be higgsino-dominated. The question then arises: what are the prospects for direct/indirect detection of relic higgsinos in WIMP detection experiments?

In Fig. 2, we show the spin-independent higgsino-proton scattering rate in  $pb$  as calculated using IsaReS[28]. The result is rescaled by a factor  $\xi = \Omega_{\tilde{Z}_1}^{std} h^2 / 0.11$  to account for the fact that the local relic abundance might be far less than the usually assumed value  $\rho_{local} \simeq 0.3 \text{ GeV}/\text{cm}^3$ , as suggested long ago by Bottino *et al.*[29] (the remainder would be composed of axions). The higgsino-like WIMP in our case scatters from quarks and gluons mainly via  $h$  exchange. The  $\tilde{Z}_1 - \tilde{Z}_1 - h$  coupling involves a product of both higgsino and gaugino components. In the case of RNS models, the  $\tilde{Z}_1$  is mainly higgsino-like, but since  $m_{1/2}$  is bounded from above by naturalness, the  $\tilde{Z}_1$  contains enough gaugino component that the coupling is never small: in the notation of Ref. [3]

$$\mathcal{L} \ni -X_{11}^h \tilde{\tilde{Z}}_1 \tilde{Z}_1 h \quad (4)$$

where

$$X_{11}^h = -\frac{1}{2} \left( v_2^{(1)} \sin \alpha - v_1^{(1)} \cos \alpha \right) \left( g v_3^{(1)} - g' v_4^{(1)} \right), \quad (5)$$

and where  $v_1^{(1)}$  and  $v_2^{(1)}$  are the higgsino components and  $v_3^{(1)}$  and  $v_4^{(1)}$  are the gaugino components of the lightest neutralino,  $\alpha$  is the Higgs mixing angle and  $g$  and  $g'$  are  $SU(2)_L$  and  $U(1)_Y$  gauge couplings. Thus, for SUSY models with low  $\Delta_{EW} \lesssim 50 - 100$ , the SI direct detection cross section is also bounded from below, even including the rescaling factor  $\xi$ .

From the Figure, we see that the current reach from 225 live-days of Xe-100 running[30] already bites into a significant spread of parameter points. The excluded points are colored green. The projected reach of the LUX 300 kg detector[31] is also shown by the black-dashed contour, which should explore roughly half the allowed RNS points. The reach of SuperCDMS 150 kg detector[32] is shown as the purple-dashed contour. The projected reach of Xe-1-ton, a ton scale liquid Xenon detector, is also shown[33]. Our main result is this: the projected Xe-1-ton detector, or other comparable noble liquid detectors, can make a *complete* exploration of the RNS parameter space. Since deployment of the Xe-1-ton detector is imminent, it seems direct WIMP search experiments may either verify or exclude RNS models in the near future, thus bringing the story of electroweak naturalness to a conclusion!

While the above result is indeed compelling, it is not a theorem, and is subject to several reasonable assumptions. These include the assumption of  $R$ -parity conservation with a higgsino-like co-DM particle, along with the assumption of non-negligible  $s \rightarrow aa$  decay rate. If the  $s \rightarrow aa$  decay rate is somehow forbidden or highly suppressed, then  $s \rightarrow gg$  (gluons) may be dominant, in which case substantial entropy dilution can still occur[24, 25].

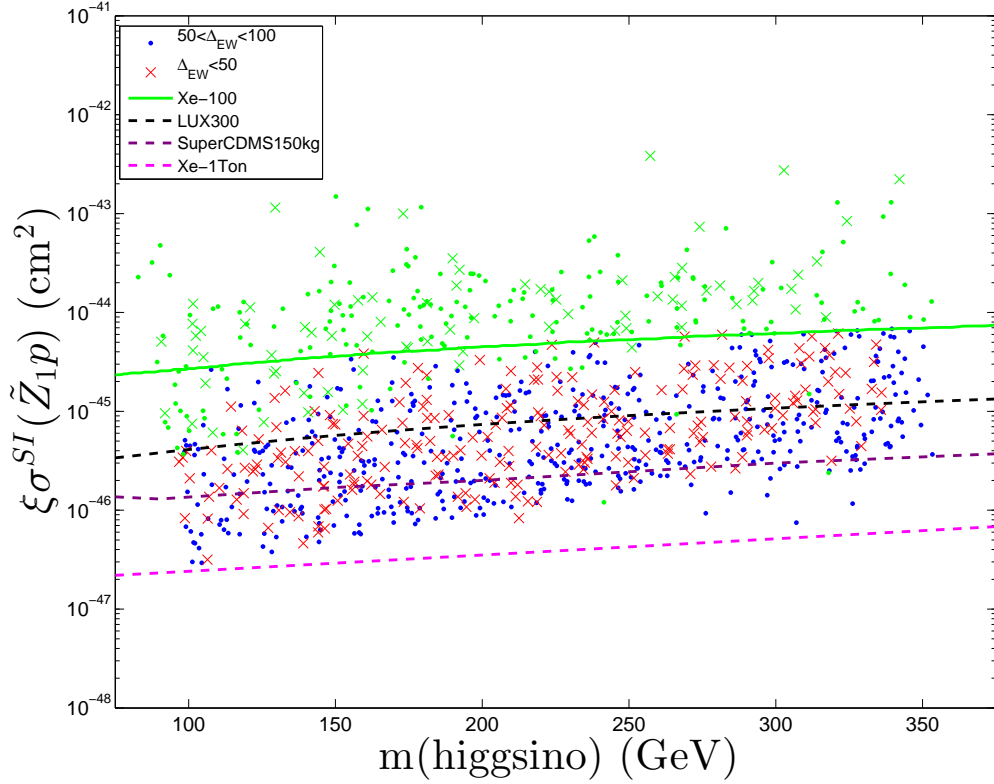


Figure 2: Plot of rescaled higgsino-like WIMP spin-independent direct detection rate  $\xi\sigma^{SI}(\tilde{Z}_1 p)$  versus  $m(\text{higgsino})$  from a scan over NUHM2 parameter space with  $\Delta_{EW} < 50$  (red crosses) and  $\Delta_{EW} < 100$  (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show the current reach from *Xe-100* experiment, and projected reaches of LUX, SuperCDMS 150 kg and *Xe-1* ton.



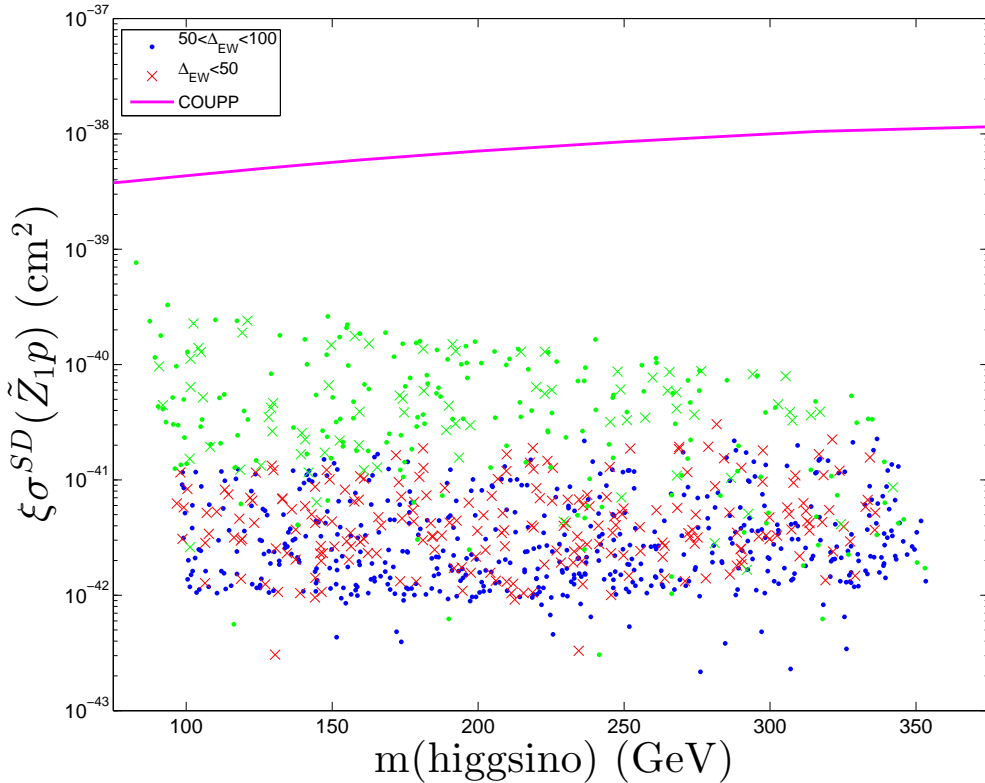


Figure 3: Plot of rescaled spin-dependent higgsino-like WIMP detection rate  $\xi \sigma^{SD}(\tilde{Z}_1 p)$  versus  $m(\text{higgsino})$  from a scan over NUHM2 parameter space with  $\Delta_{EW} < 50$  (red crosses) and  $\Delta_{EW} < 100$  (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show current reach from the COUPP detector.

An alternative method for rescuing theories with an underabundance of WIMPs is to hypothesize the existence of some scalar field (such as a modulus field from string theory) which can be produced via coherent oscillations, and which can engage in late decays injecting either more WIMPs (thus increasing the WIMP abundance) or entropy (thus decreasing the abundance[34]). The resulting abundance just depends on two parameters: the scalar field decay temperature and the branching fraction into SUSY particles[35, 36, 37, 38]. In our case, with a higgsino-like WIMP underabundance, the decaying scalar field would increase the higgsino abundance to its measured value, and the rescaling factor  $\xi = 1$ . For this possibility, the results of Ref. [12] would apply.

In Fig. 3, we show the rescaled *spin-dependent* higgsino-proton scattering cross section  $\xi \sigma^{SD}(\tilde{Z}_1 p)$ . Here we show recent limits from the COUPP[39] detector. Current limits are still about an order of magnitude away from reaching the predicted rates from RNS models.

To compare against the current reach of IceCube[40], we show in Fig. 4 the value of  $\sigma^{SD}(\tilde{Z}_1 p)$ , with no rescaling factor. Here, the IceCube rates should not be rescaled since the IceCube detection depends on whether the Sun has equilibrated its core abundance between capture rate and annihilation rate[41]. Typically for the Sun, equilibration is reached for almost



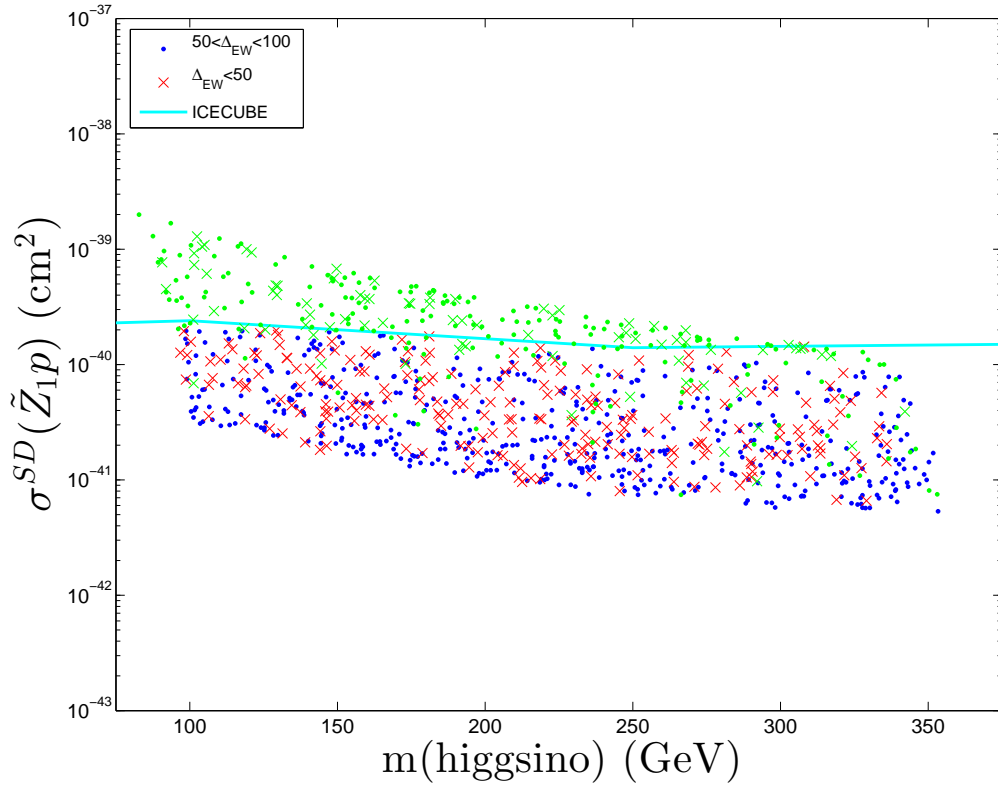


Figure 4: Plot of (non-rescaled) spin-dependent higgsino-like WIMP detection rate  $\sigma^{SD}(\tilde{Z}_1 p)$  versus  $m(\text{higgsino})$  from a scan over NUHM2 parameter space with  $\Delta_{EW} < 50$  (red crosses) and  $\Delta_{EW} < 100$  (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show current reach from IceCube.

all of SUSY parameter space[42]. The IceCube limits have entered the RNS parameter space and excluded the largest values of  $\sigma^{SD}(\tilde{Z}_1 p)$ .

In Fig. 5, we show the rescaled thermally-averaged neutralino annihilation cross section times relative velocity in the limit as  $v \rightarrow 0$ :  $\xi^2 \langle \sigma v \rangle|_{v \rightarrow 0}$ . This quantity enters into the rate expected from WIMP halo annihilations into  $\gamma$ ,  $e^+$ ,  $\bar{p}$  or  $\bar{d}$ . The rescaling appears as  $\xi^2$  since limits depend on the square of the local WIMP abundance[43]. Anomalies in the positron and  $\gamma$  spectra have been reported, although the former may be attributed to pulsars[44], while the latter 130 GeV gamma line may be instrumental. Soon to be released results from AMS-02 should clarify the situation. On the plot, we show the limit derived from the Fermi LAT gamma ray observatory[45] for WIMP annihilations into  $WW$ . These limits have not yet reached the RNS parameter space due in part to the squared rescaling factor.

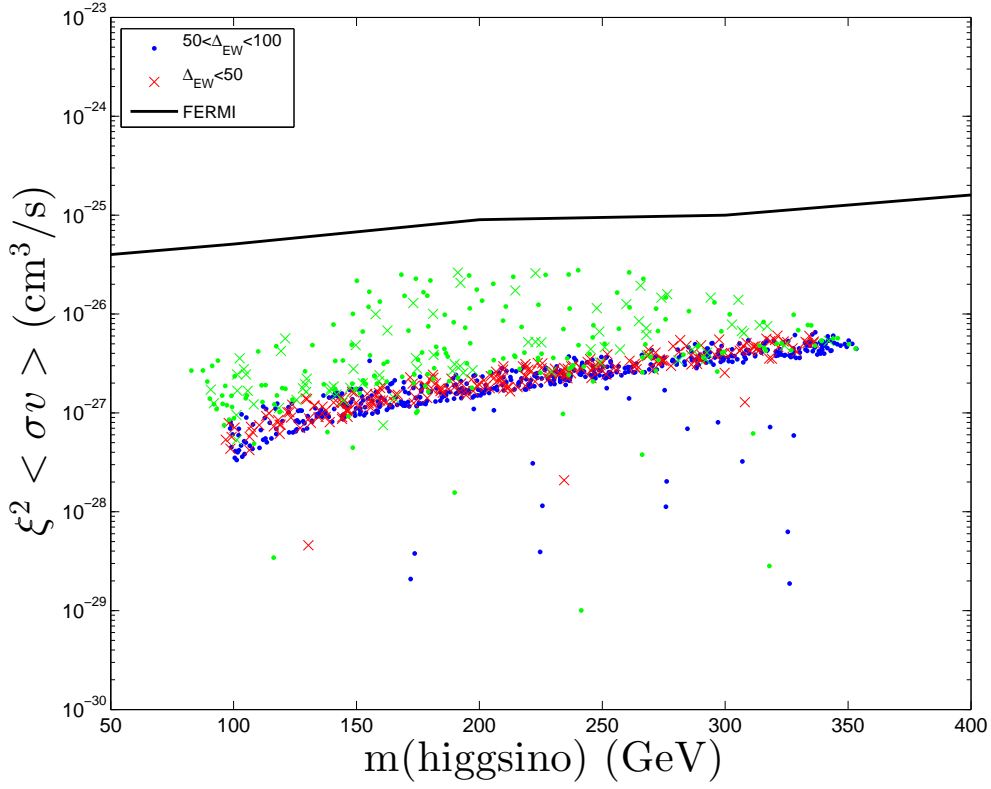


Figure 5: Plot of rescaled  $\xi^2 \langle \sigma v \rangle|_{v \rightarrow 0}$  versus  $m(\text{higgsino})$  from a scan over NUHM2 parameter space with  $\Delta_{EW} < 50$  (red crosses) and  $\Delta_{EW} < 100$  (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show current reach from Fermi LAT, Ref. [45].

### 3 Conclusions:

In conclusion, we have found that SUSY models can elude the Little Hierarchy Problem in the guise of radiative natural SUSY models which feature a mainly higgsino-like neutralino that may act as a co-dark-matter particle along with the axion. While LHC can explore a portion of RNS parameter space, an ILC can probe it entirely, although such a machine may be well over a decade in the future. However, current WIMP direct detection experiments are biting into the meat of RNS parameter space, even if we take into account rescaling of the local abundance due to the fact that higgsinos may make up only a portion of the dark matter. LUX and ultimately SuperCDMS will probe further. The soon-to-be-deployed Xe-1-ton noble liquid detector should be able to *completely* explore the entire RNS parameter space (as shown in Fig. 2), thus either discovering a higgsino-like WIMP or rejecting the story of SUSY electroweak naturalness. Complementary signals from spin-dependent and indirect WIMP detection channels are less likely since these are usually suppressed by the reduced local WIMP density which is expected from models of mixed dark matter.

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